CHIME, and future possibilities for 21-cm

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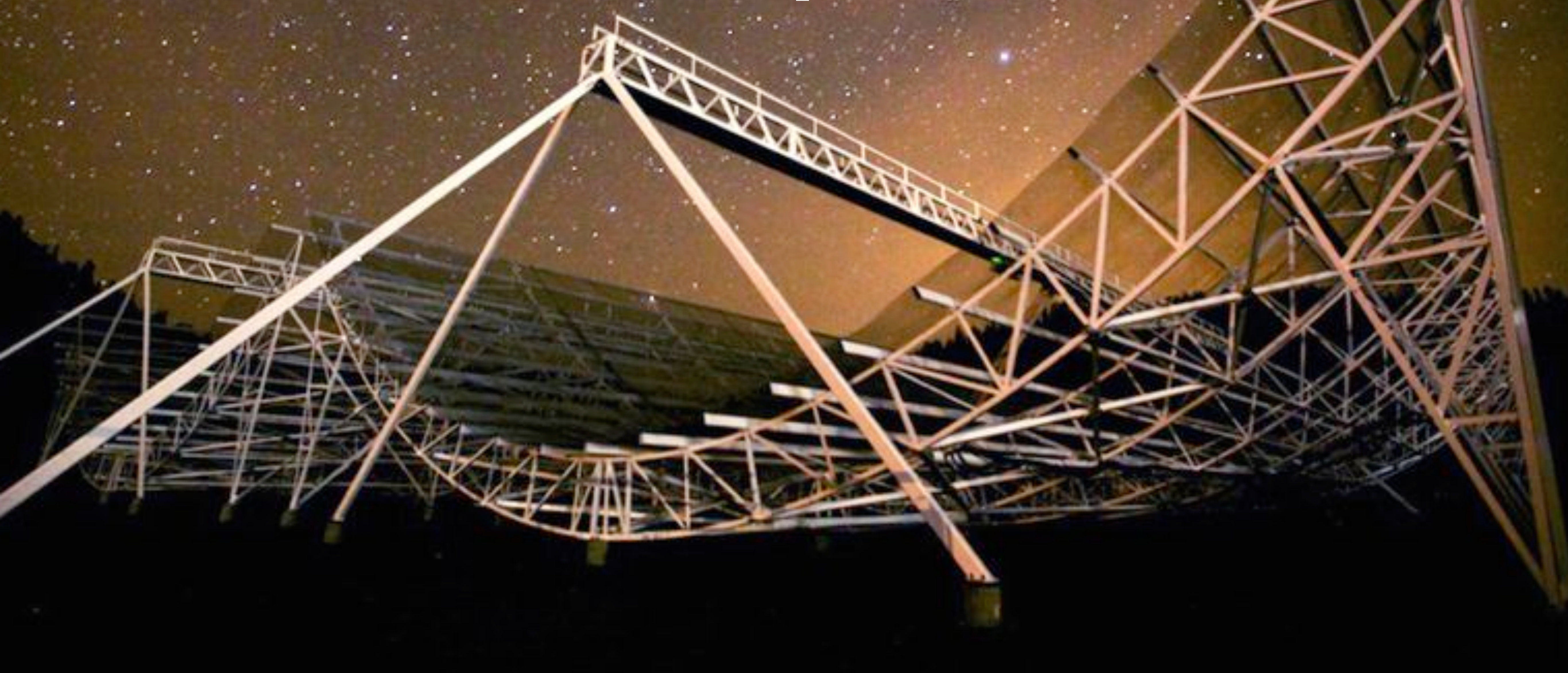
on behalf of the CHIME collaboration
Brookhaven, September 2015



chime

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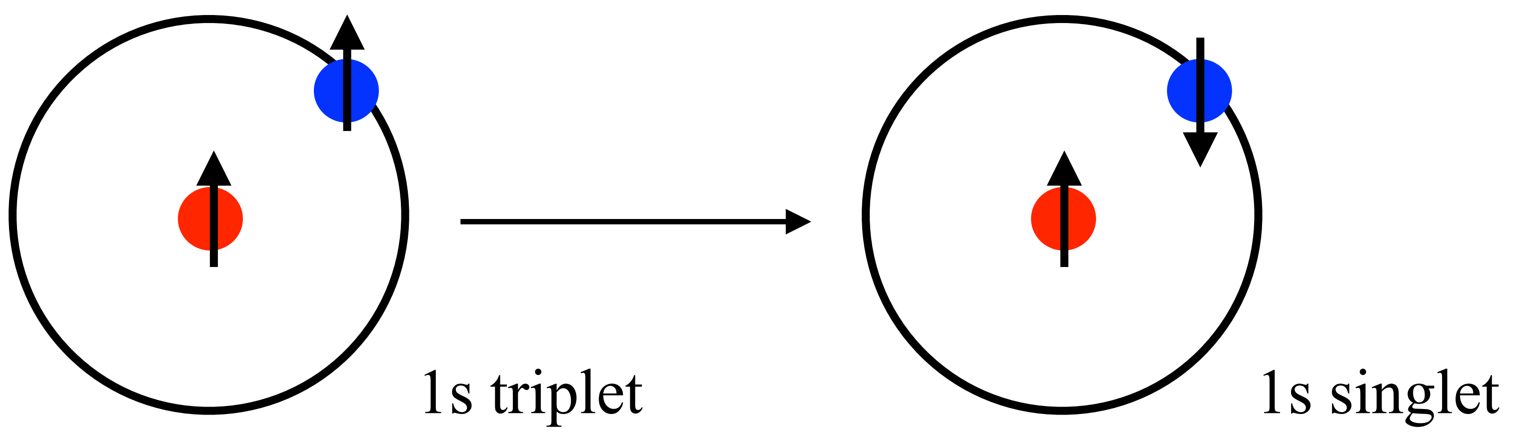
21-cm emission as a tracer of large-scale structure

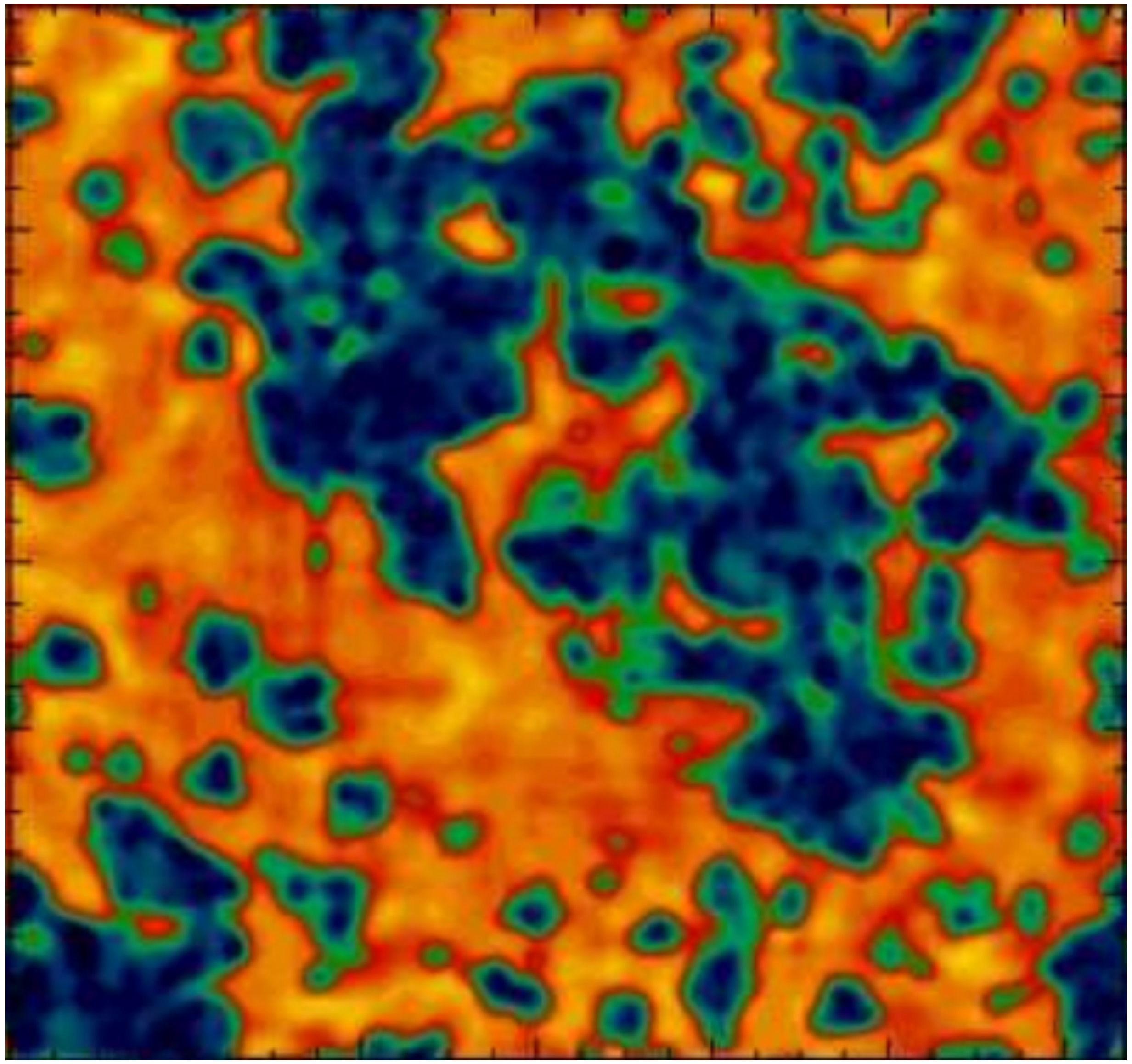
Neutral hydrogen (HI) has a long-lived emission line at λ_0=21cm



Intensity mapping: by observing the radio sky as a function of angle θ,ϕ and wavelength λ, one can make a 3D map of fluctuations in HI density (or HI thermal state).

21-cm emission as a tracer of large-scale structure

At high redshifts ($5 \lesssim z \lesssim 12$), HI fluctuations are mainly sourced by reionization bubbles; we get a map of patchy reionization.

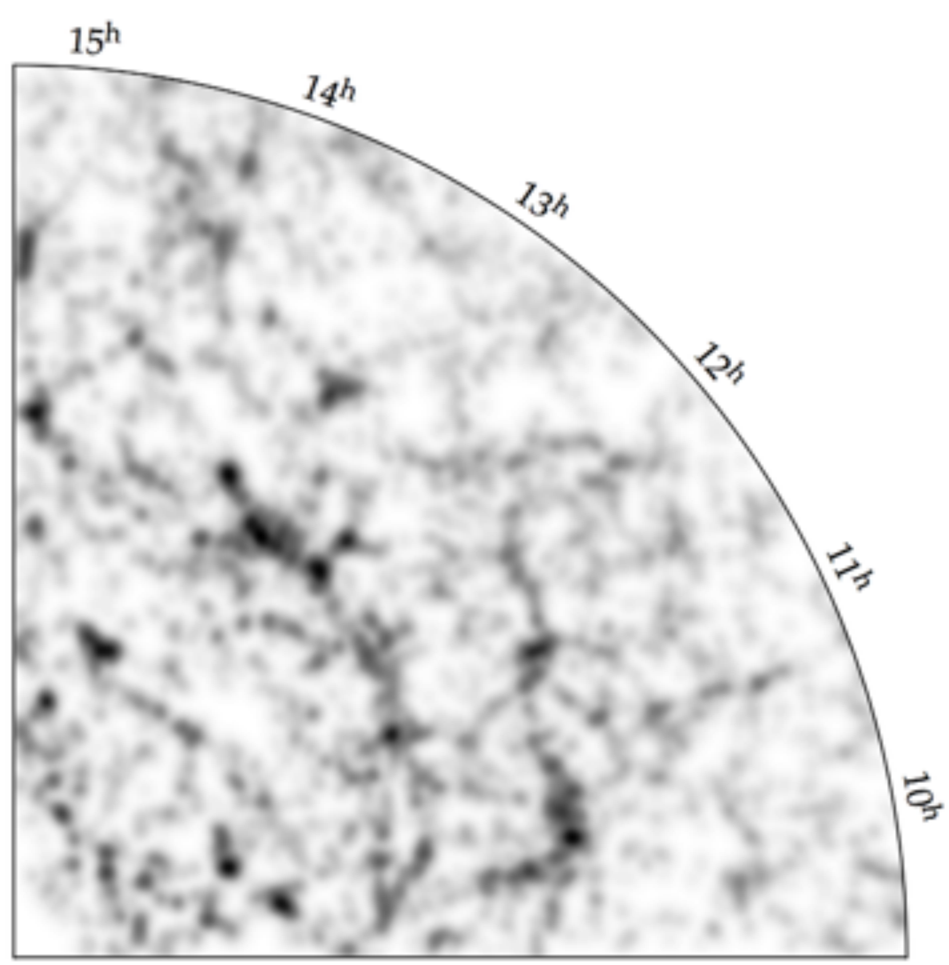


Ciardi & Madau 2003

21-cm emission as a tracer of large-scale structure

At low redshifts, hydrogen is mostly ionized. Some HI survives in "self-shielding" systems. (CHIME: $0.8 \leq z \leq 2.5$)

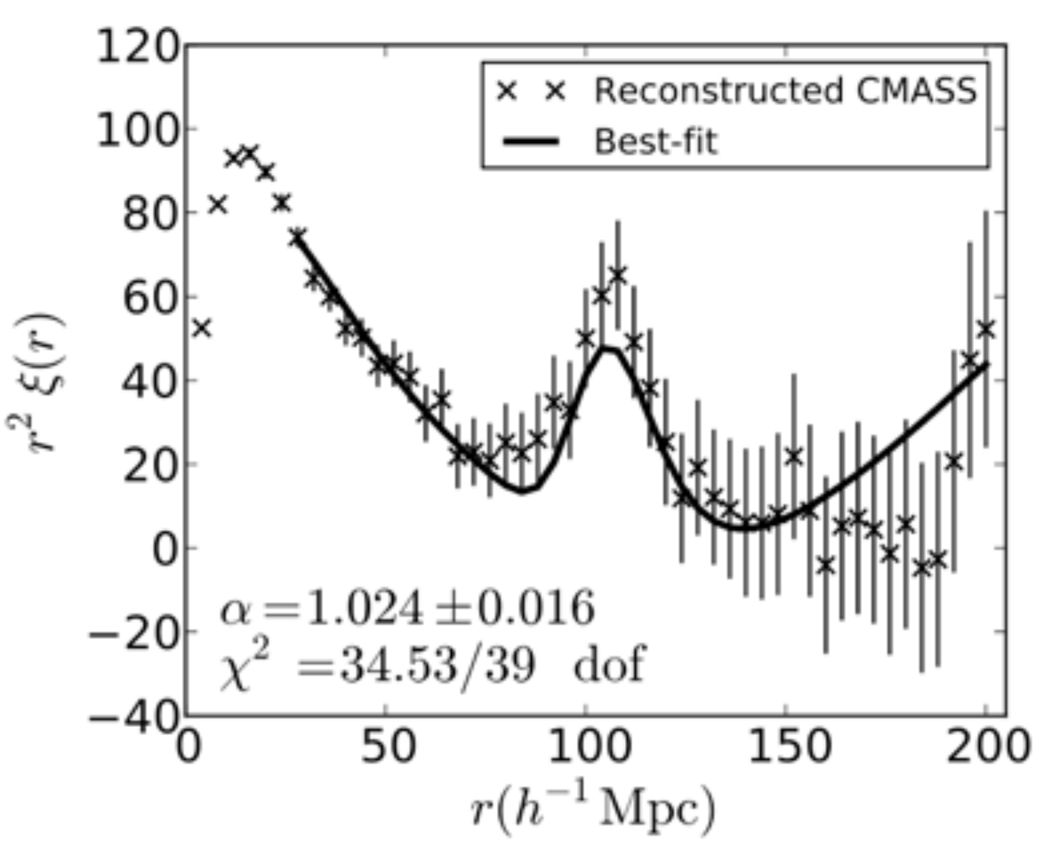
Since HI systems trace large-scale structure, we get a 3D map of the cosmological density field (individual HI systems unresolved)



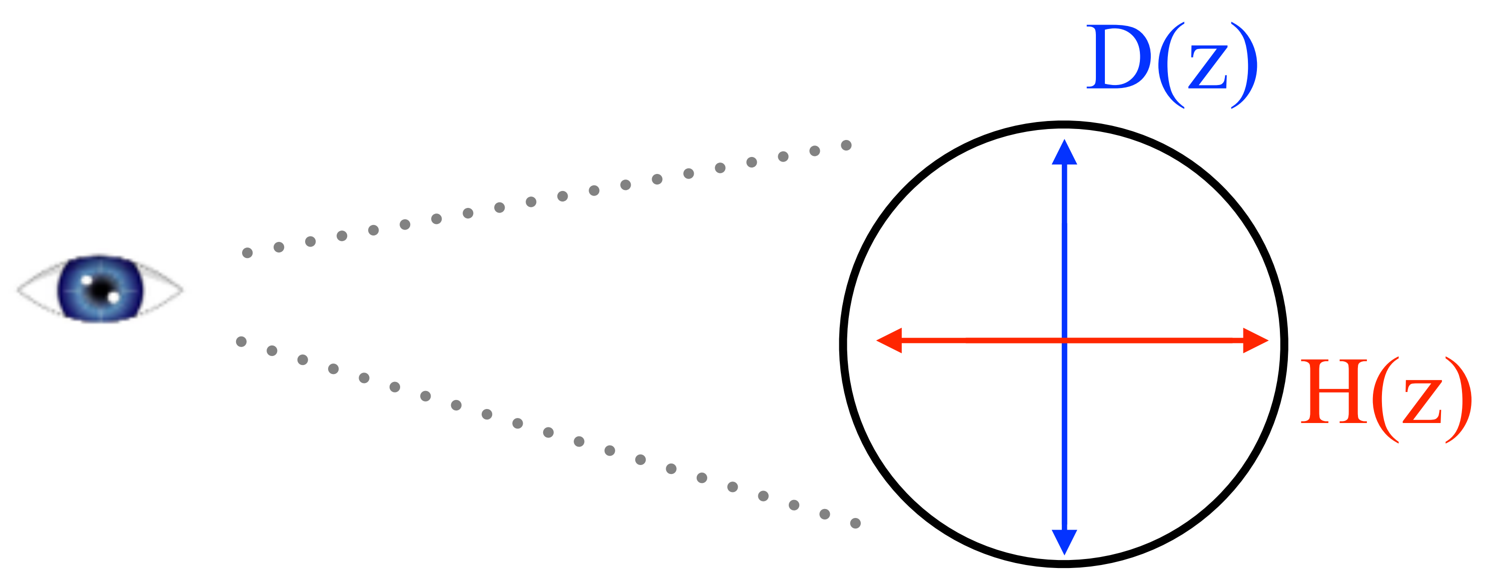
21-cm emission as a tracer of large-scale structure

Can use this 3D map to do large-scale structure: baryon acoustic oscillations, lensing, redshift-space distortions, etc.

Main goal of CHIME is to measure the BAO "standard ruler"

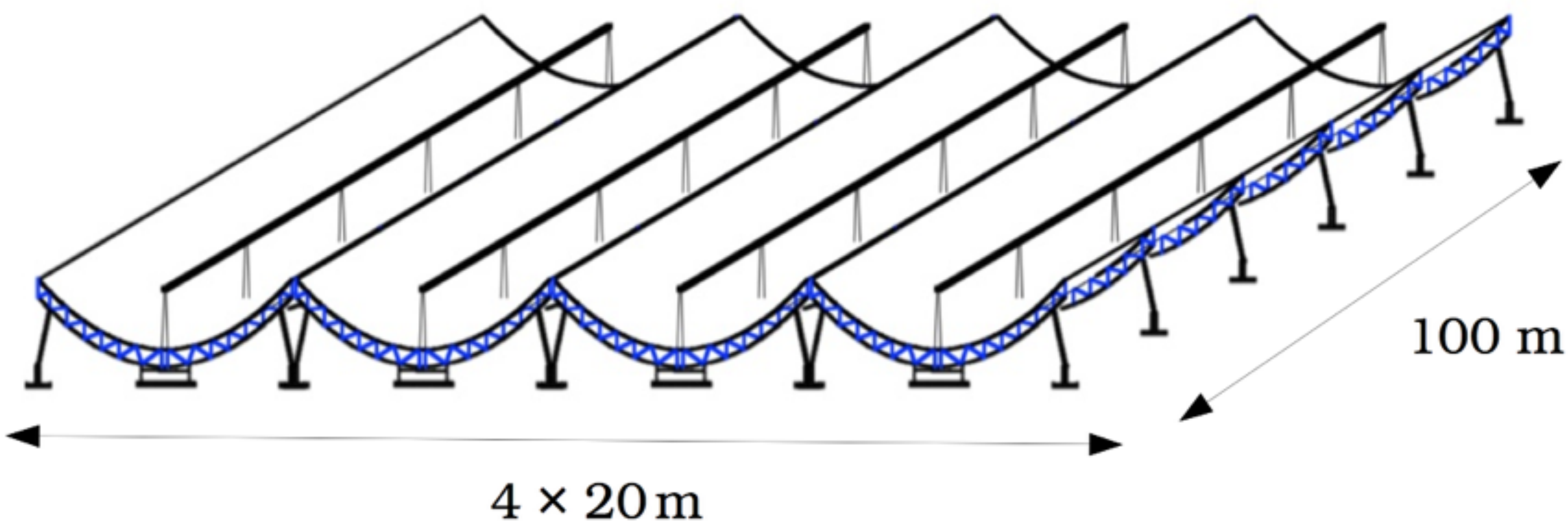


SDSS (2012)



CHIME

- No moving parts, sky is surveyed via Earth rotation
- Angular resolution ~1/3 deg
- Radial resolution is much higher, but long-wavelength radial modes are lost due to foreground removal (more on this later)
- Frequency range 400-800 MHz (redshift $0.8 \leq z \leq 2.5$)
- Full instrument under construction (1024 feeds, 80x100 m^2)
- "Pathfinder" instrument running! (1/8 scale of full instrument)

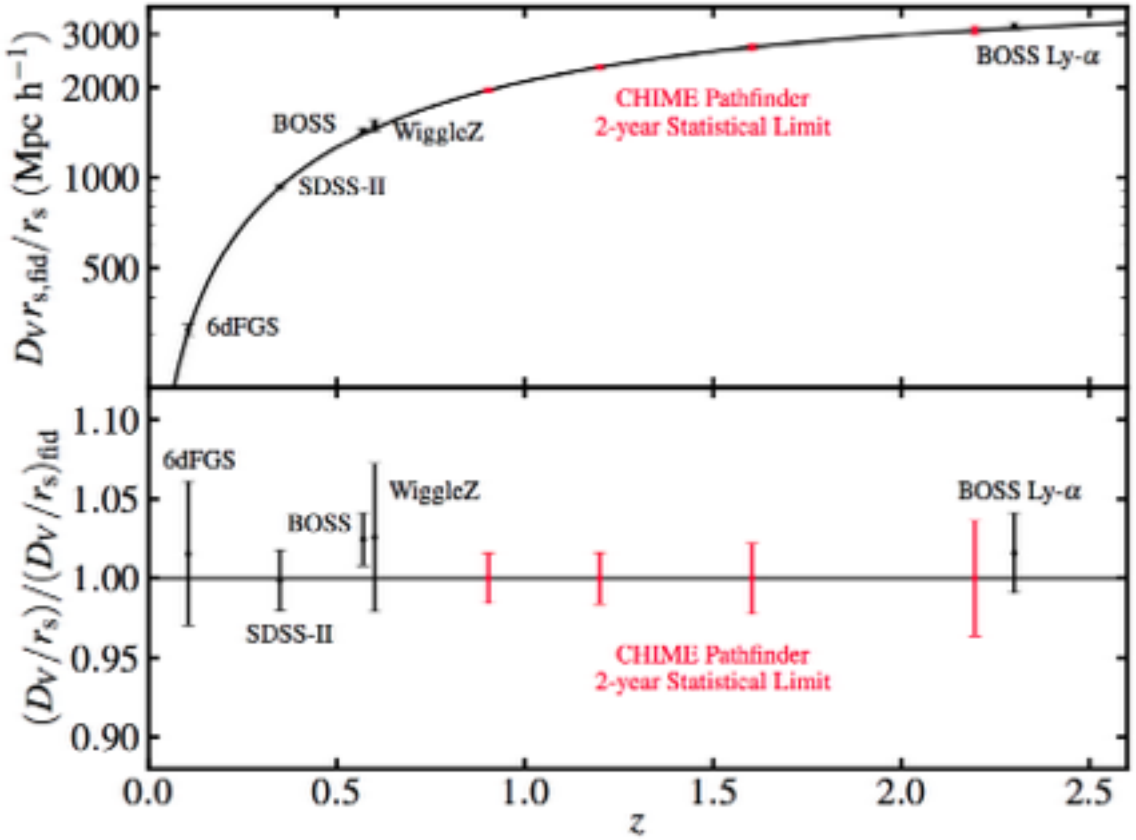


BAO forecasts

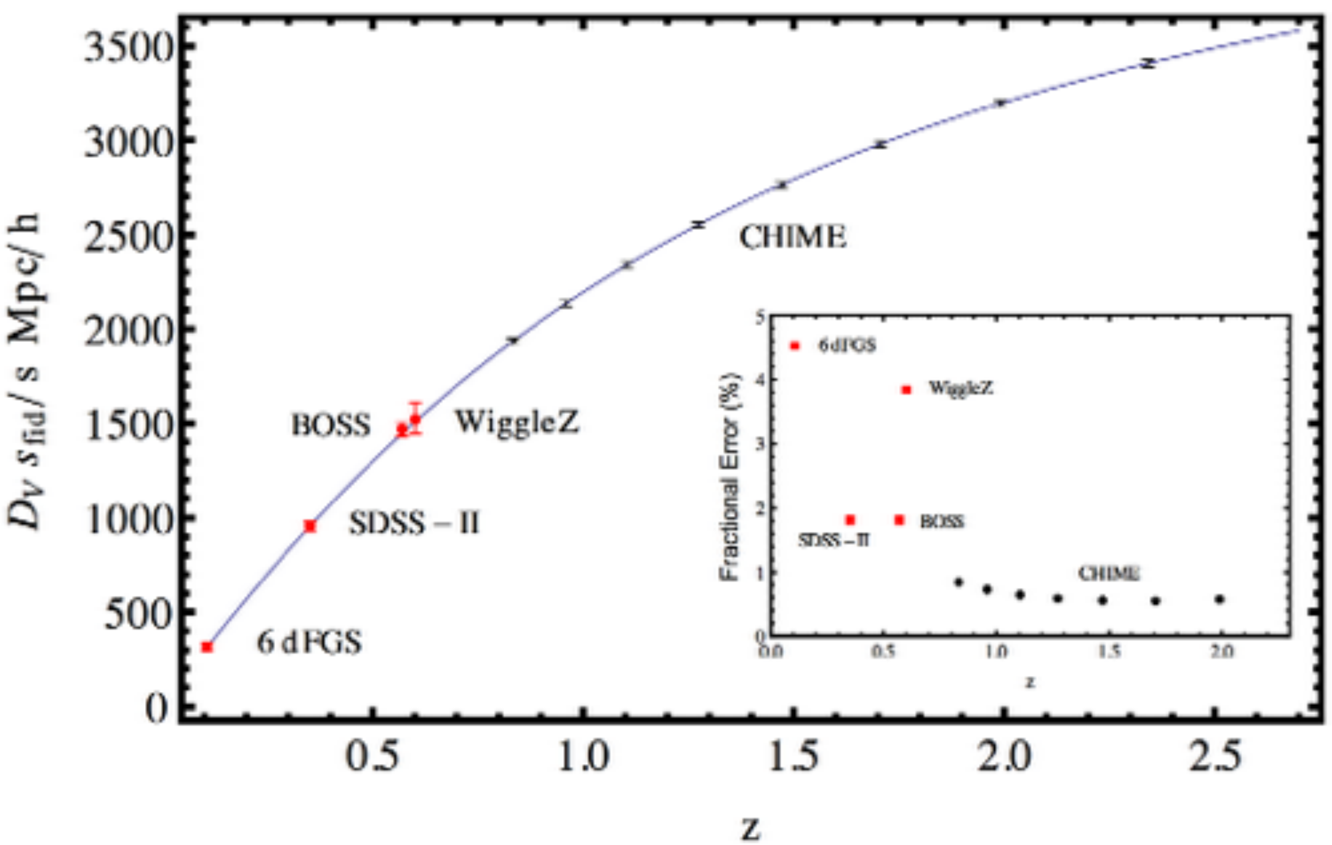
The CHIME pathfinder is an interesting BAO experiment, comparable to current surveys.

Full CHIME is a Stage-IV dark energy experiment!

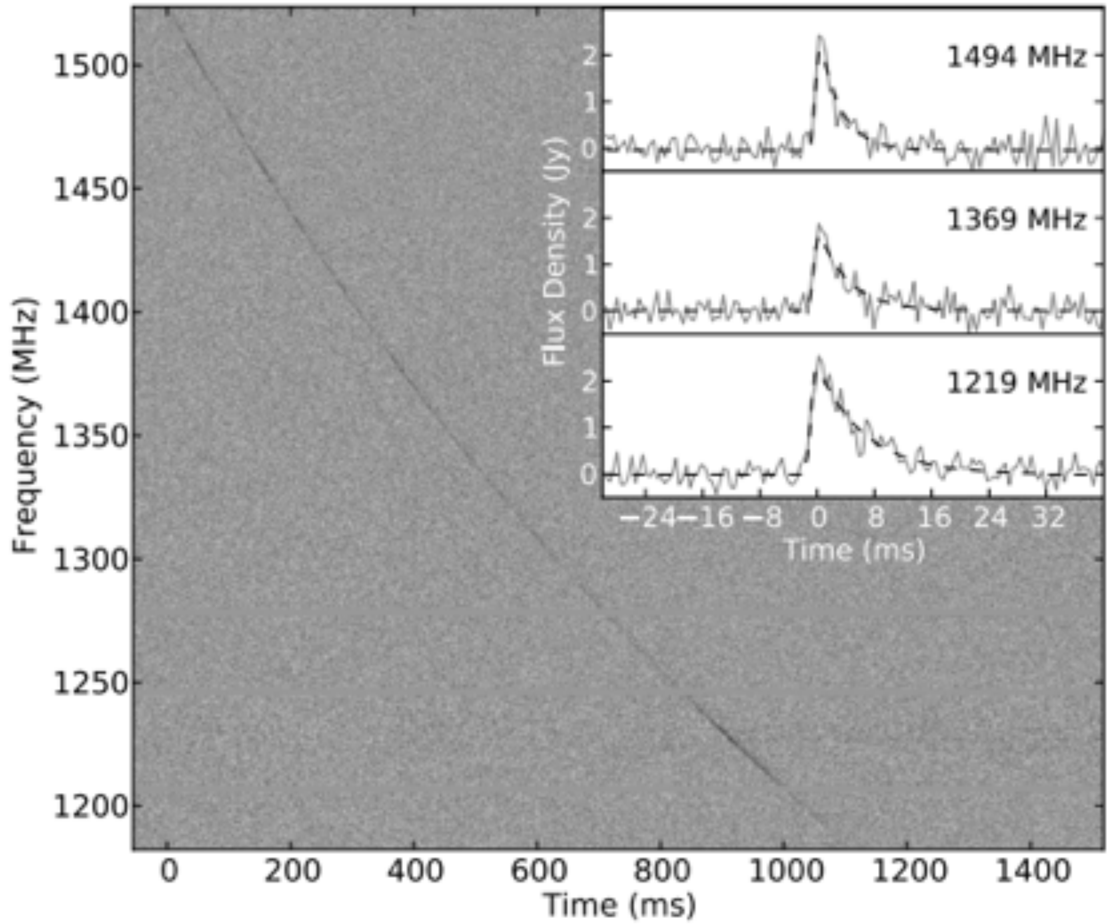
CHIME pathfinder



Full CHIME

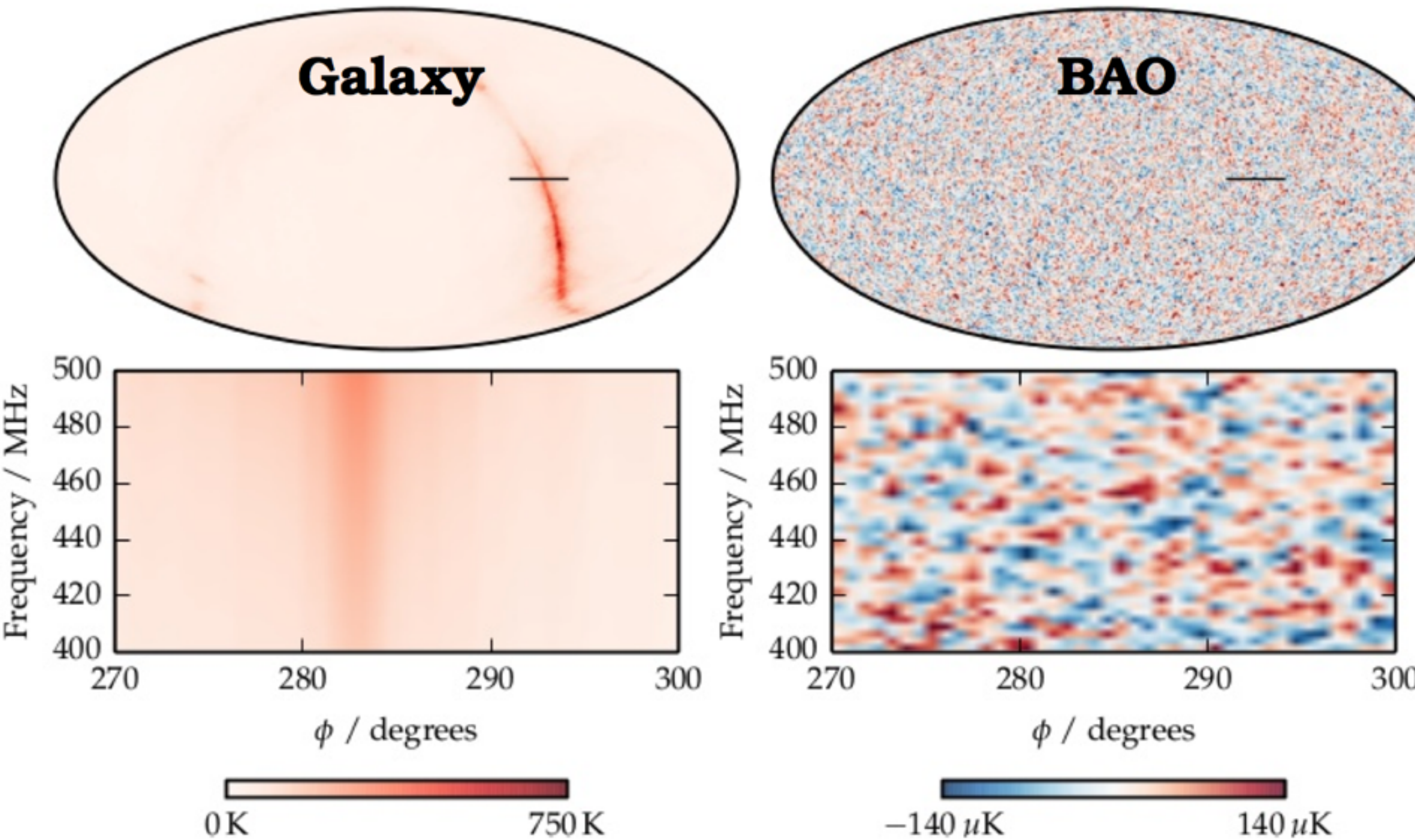


Fast radio bursts



	DM (pc cm	z
FRB0102	375	~0.3
FRB1102	944	~0.81
FRB1106	723	~0.61
FRB1107	1103	~0.96
FRB1201	553	~0.45
FRB1211	557	~0.26

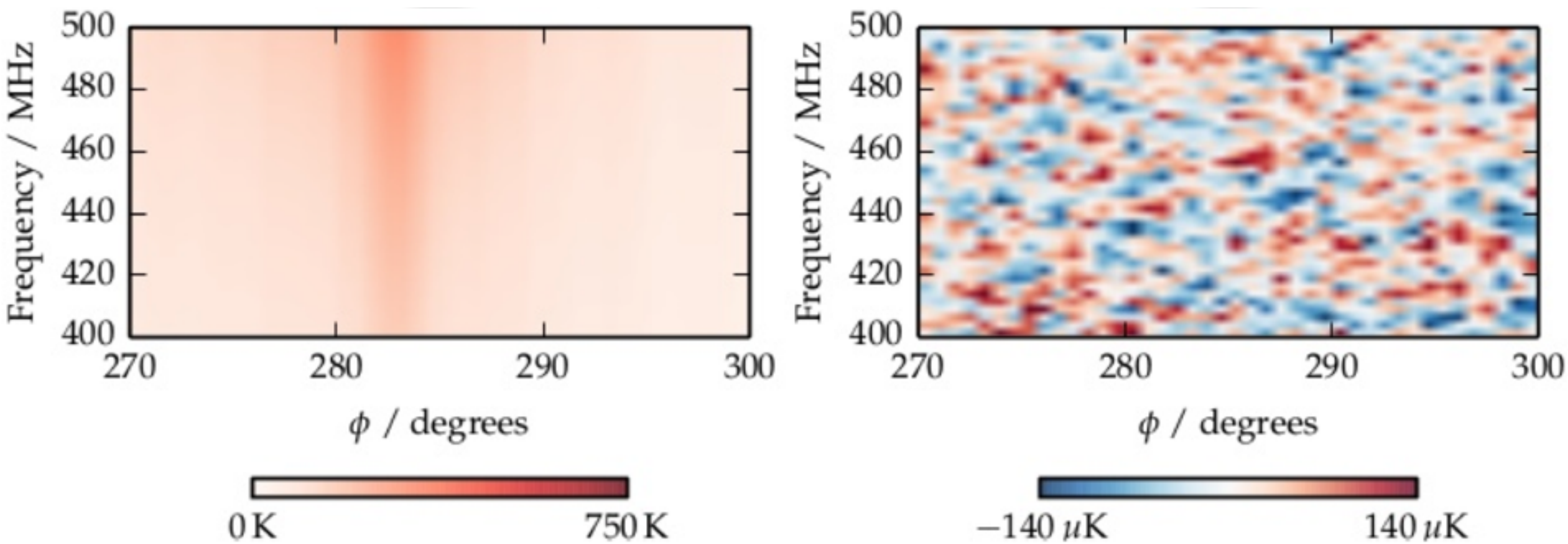
Foregrounds: the reason this is hard



Foregrounds: the reason this is hard

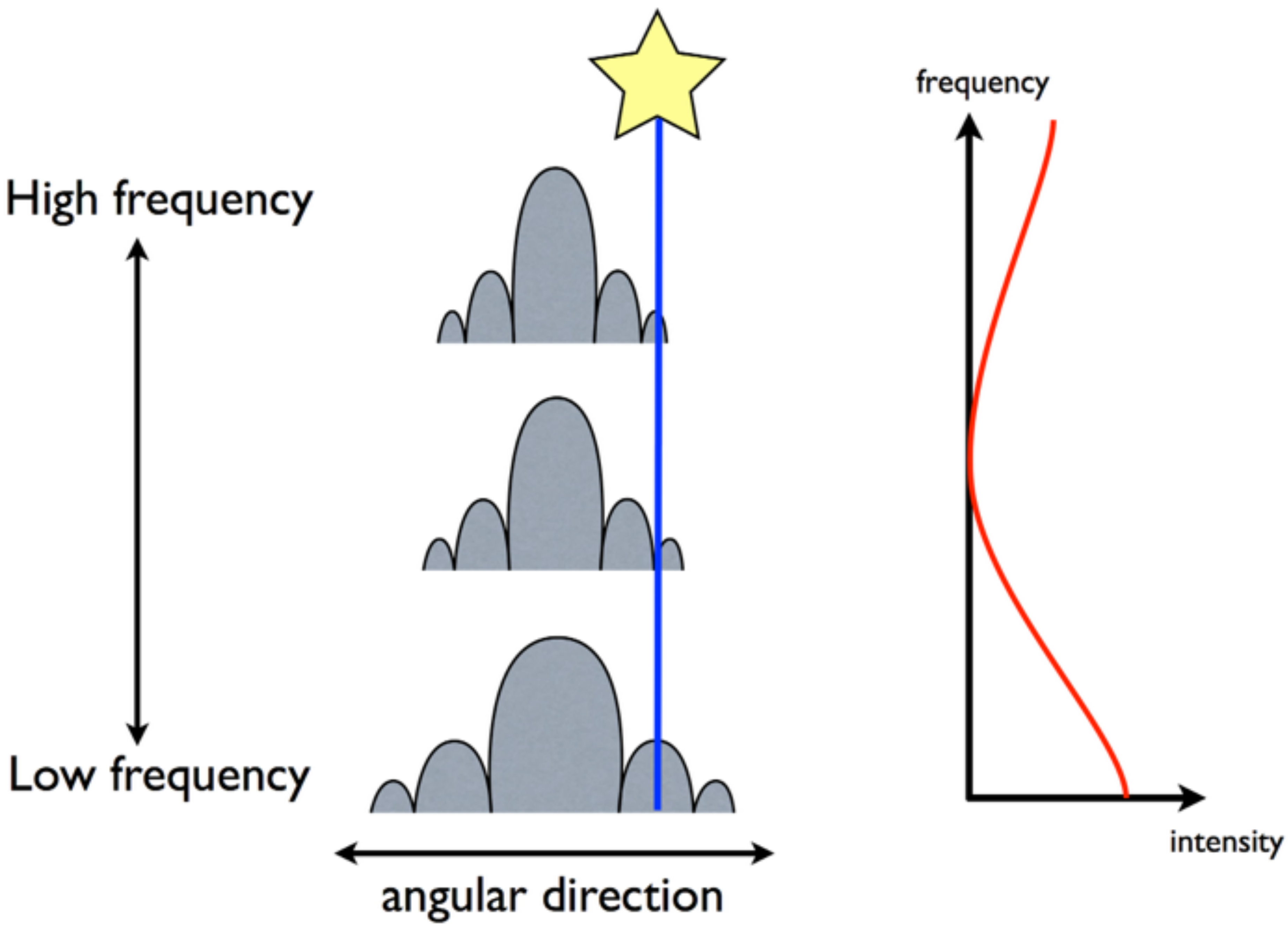
Strategy: radio foregrounds are very spectrally smooth, whereas 21-cm anisotropy has small-scale power in the frequency (radial) direction.

So foregrounds and 21-cm can be separated by high-pass filtering along the frequency axis.



Foregrounds: the reason this is hard

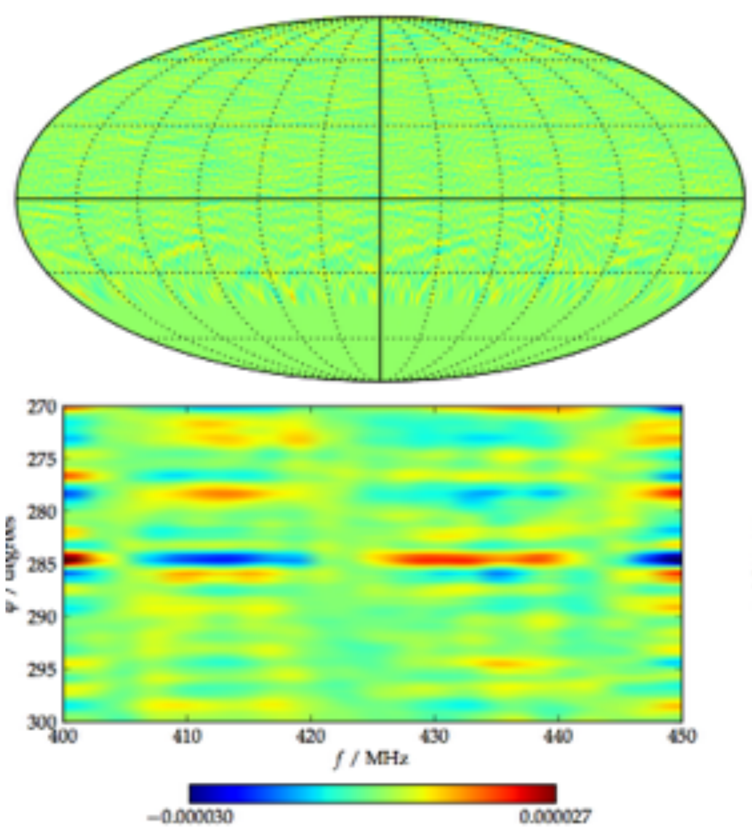
Problem: beam is frequency-dependent (diffractive) which leads to mode mixing. Naive high-pass filtering doesn't work.



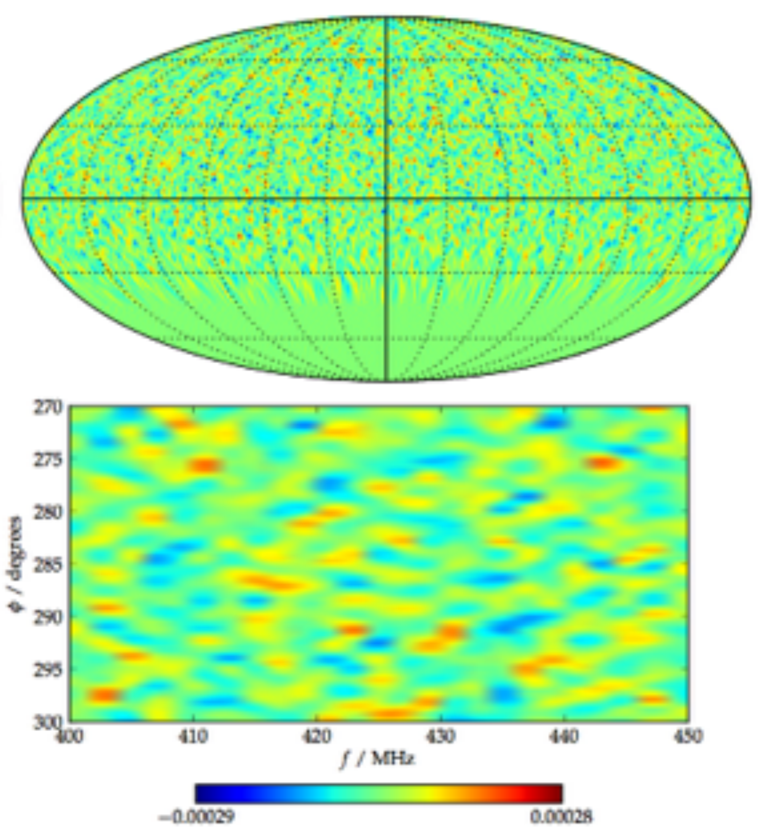
Foregrounds: the reason this is hard

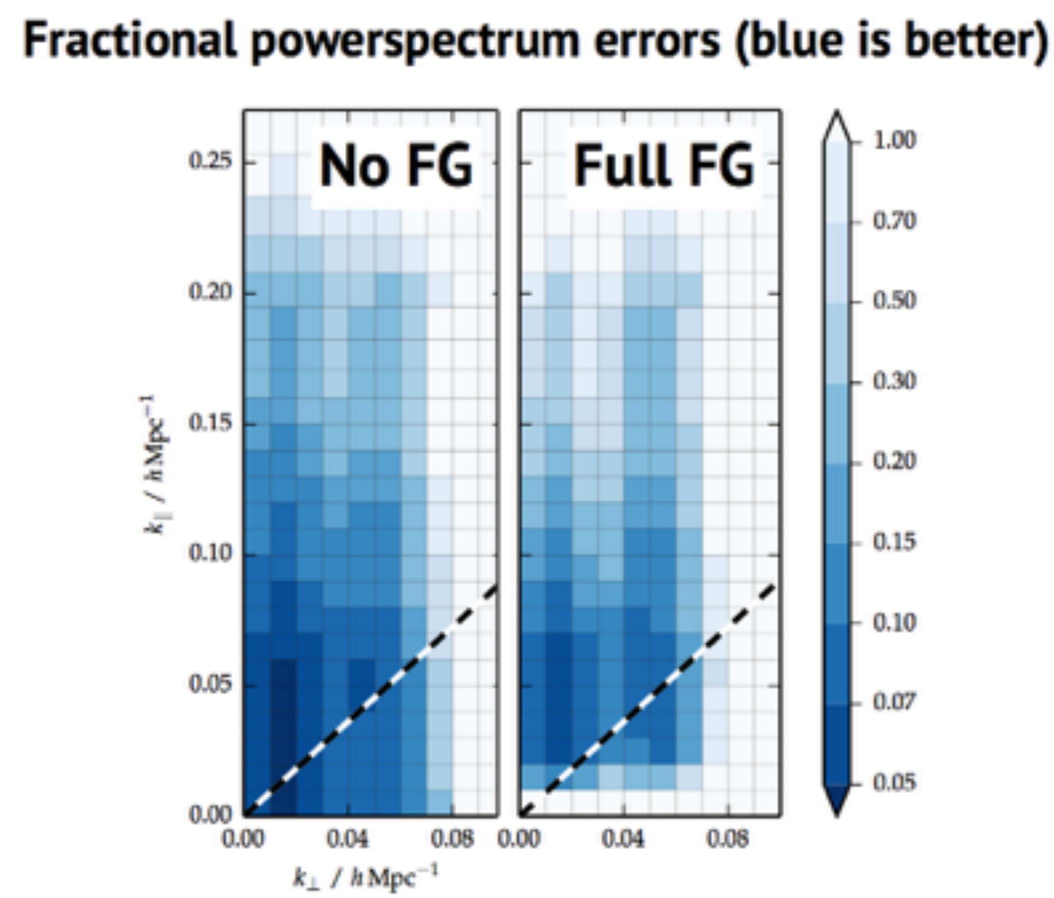
Shaw et al 2013, 2014: can separate foregrounds and 21-cm by linear algebra tricks if the instrument is perfectly characterized. (Key idea: use block diagonality in m)

Galaxy



21-cm





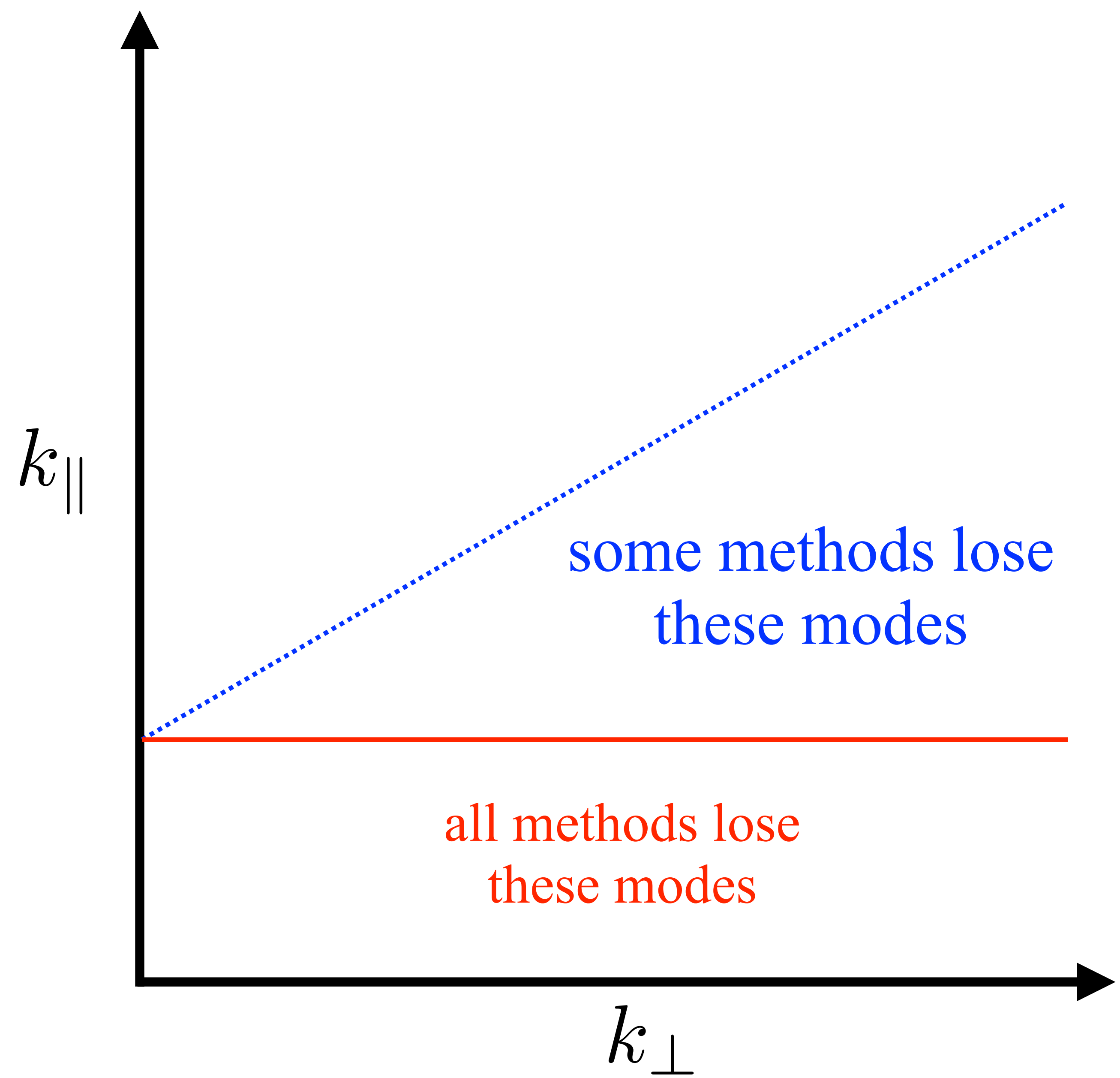
S/F > 10

Foregrounds: the reason this is hard

Instrument must be very well-characterized. From sims:
- Calibration requirement (complex gains) ~1%
- Beam modeling requirement ~0.1%

Other methods are suboptimal but require less precise modeling:

- Foreground "wedge"?
- Delay-space filtering?



CHIME is an enormous computation:
- Total bandwidth 6.4 Tbps (global internet: ~250 Tbps!)
- Correlator is ~7 petaflops (achieved by bit-packing tricks)
- Reduced data is tens of TB per day

Moore's law: key computing parameters (e.g. flops/watt, network speed, memory bandwidth) increase exponentially with doubling time $T_{Moore} \sim 24$ months.

In CHIME, data from one antenna can be processed with a modest amount of cheap commodity hardware:
- one inexpensive GPU
- one 10 Gbps ethernet card
- 1/8 of an FPGA board

Thanks to Moore's law, the computing cost is now comparable to the antenna/telescope cost; this is what makes CHIME possible.

The 21cm (auto) power spectrum hasn't been detected yet, but we hope to measure it well enough to be a stage-IV dark energy experiment! (CMB analog: pre-COBE→Planck in one experiment?)

Looking to the future, if CHIME works well, cost of scaling up the collecting area A is either

- proportional to A, or (e.g. reflector)
- proportional to A $\exp(-T/T_{\mathrm{Moore}})$! (e.g. correlator)

Most scalable way to measure more large-scale structure modes

A huge volume is potentially measurable

Can try to map
(1) low-z
(2) reionization
(3) dark ages
… although foreground temperature varies as $T \sim (1+z)^{2.5}$

At high z, the power spectrum goes out to very high k, so there is essentially no fundamental limit on how many modes we might measure

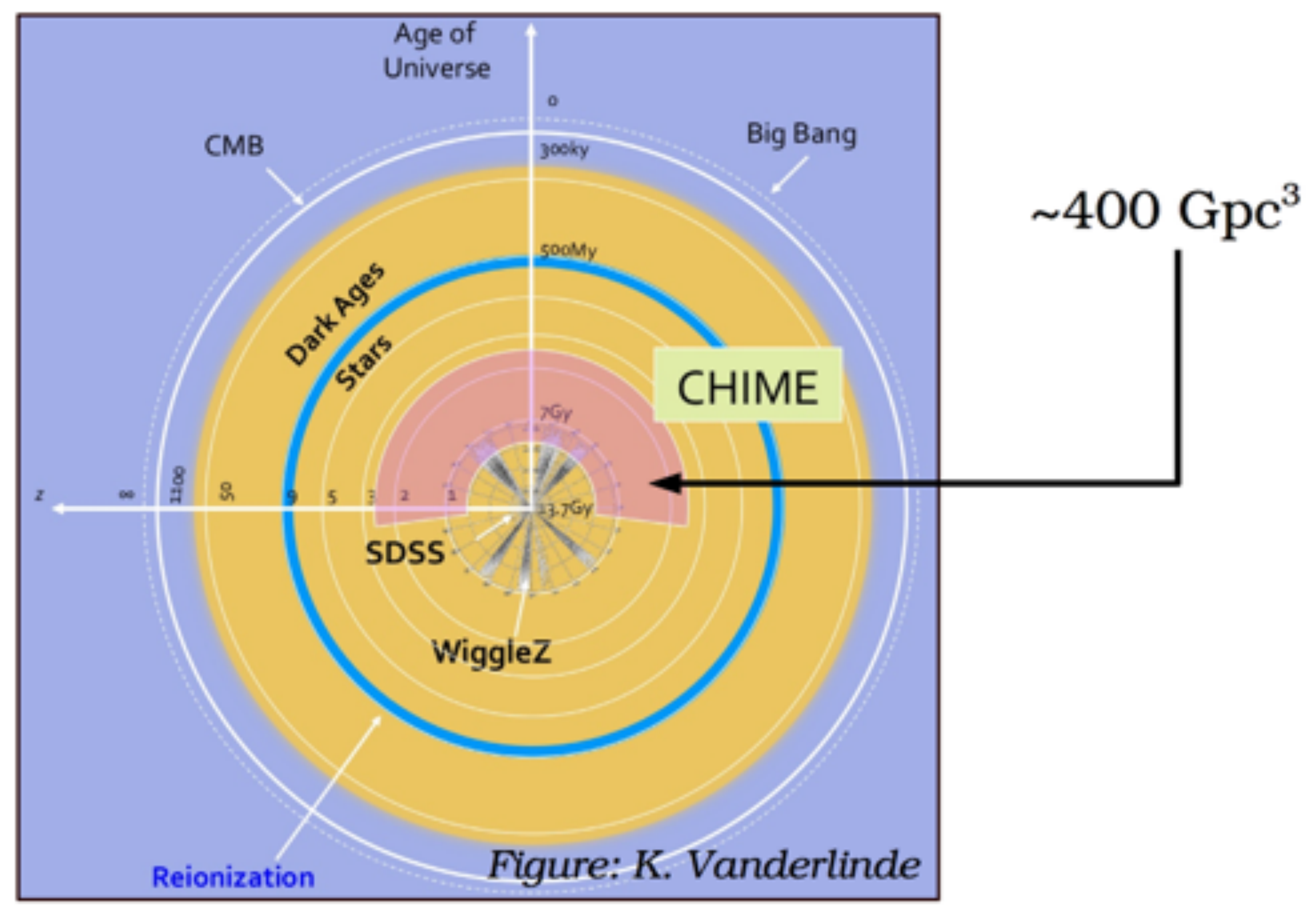


Figure: K. Vanderlinde

Some science that could be done with new 21-cm instruments, subjectively ranked from easiest to hardest:

- fast radio bursts
- pulsar searches(?) and timing
- cross correlations with other probes (e.g. spectroscopic quasars)
- BAO
- various quadratic estimators (e.g. gravitational lensing reconstruction / tidal reconstruction)
- redshift space distortions
- broadband power spectrum (neutrino mass etc.)
- primordial non-Gaussianity


Thanks!